SSC-207

EFFECT OF FLAME AND MECHANICAL STRAIGHTENING ON MATERIAL PROPERTIES OF WELDMENTS

SHIP STRUCTURE COMMITTEE

1970

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Dear Sir:

Owing to the absence of specific information on the effects of various thermal and mechanical means for removing distortions in high-strength steels fabricated in ship hulls, severe cautionary methods have been employed. Such methods add to the growing list of increasing expenses for ship construction. In order to alleviate this situation, the Ship Structure Committee has undertaken a project to develop information whereby a reassessment can be made as to whether severe material degradation occurs in removing distortions through conventional methods.

Herewith is a summary report of a first year's effort providing some indication that less stringent requirements may be possible for certain families of steels.

Sincerely,

W. F. Rea, III
RADM, U.S. Coast Guard
Chairman, Ship Structure Committee

SSC-207

Summary Report

to the

Ship Structure Committee

on

Project SR-185, "Straightening Distorted Weldments"

EFFECT OF FLAME AND MECHANICAL STRAIGHTENING ON MATERIAL PROPERTIES OF WELDMENTS

by

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Battelle Memorial Institute
Columbus, Ohio

under

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U.S. Coast Guard Headquarters
Washington, D.C.

1970

ABSTRACT

An experimental study was conducted to determine the effects of mechanical straightening and flame straightening on the properties of steels used in shipbuilding. The steels investigated during this program included an ordinary carbon steel (ABS-B), two low-alloy, high-strength steels (A441 and A537), and a quenched and tempered steel (A517, Grade A). The removal of distortion in unwelded and welded test plates was accomplished by (1) mechanical straightening at room temperature, 1000 F, 1300 F, and (2) flame straightening in the temperature ranges of 1100-1200 F and 1300-1400 F. Controlled amounts of distortion were provided in unwelded plate by mechanical bending; distortion in welded plates was provided by jigging the restraint control. Drop-weight tear tests were conducted to assess the effect of the straightening parameters on the notch-toughness behavior of the respective steels.

The notch-toughness properties of A517, Grade A decreased markedly when flame straightening was done at 1300-1400 F; somewhat less effect was observed when A517, Grade A test plates were straightened at 1100-1200 F. The notch-toughness of A517, Grade A was affected significantly by the time required for straightening. The impact properties of A537, A441, and ABS-B steels were not affected seriously by flame straightening. Mechanical straightening had little effect on the notch-toughness properties of any of the steels, because the time required for heating and straightening was minimized.

A summary report on flame straightening was prepared and distributed earlier during this program. This report discussed the nature of distortion and of flame straightening and was published as Report SSC-198. However, since very little information in the literature pertains directly to possible material degradation caused by flame straightening, the experimental studies described in this report were undertaken.

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INTRODUCTION

Distortion is a perennial problem in the shipbuilding industry, and extensive research has been undertaken to determine the causes of distortion and to minimize its occurrence. While distortion can be produced by any of the fabrication methods used in shipbuilding, its principal cause today is welding. Welding is used extensively in modern shipyards because of its advantages over other assembly methods. However, as with any complex structure, distortion is encountered when ship hulls and other structural sections are assembled by welding. The amount of distortion can be controlled and minimized by proper design and careful attention to the details of welding, but some distortion inevitably occurs. When the degree of distortion exceeds recognized acceptance standards, it must be removed.

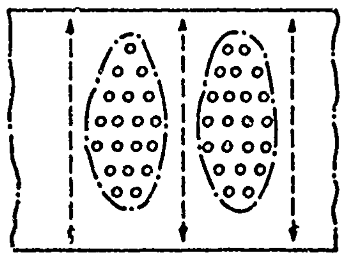
Distortion can be removed by producing adequate plastic deformation in the distorted member or section. The required amount of plastic deformation can be obtained by the thermal or mechanical methods discussed in the following paragraphs:

(1) Thermal Straightening. Thermal or flame straightening has been used most successfully in the shipbuilding industry to remove distortion. The area to be straightened is heated to about 1100-1200 F and then quenched with a water spray; repeated applications of heat in specific areas in a selected sequence or pattern are normally needed to straighten a distorted member or structure. The patterns are usually variations of the spot or linear heating techniques shown in Figure 1.

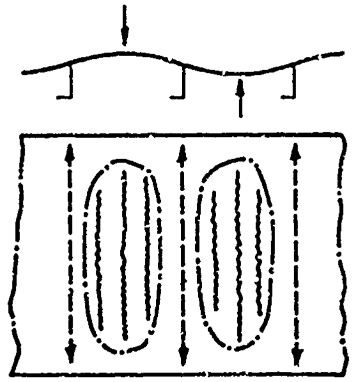
(2) Pressing. Distorted members can be straightened in a press if the members can be moved and if the press is large enough to handle them; heat may or may not be required for straightening.

(3) Other Methods. Jacking is closely related to pressing in that distortion is removed by the application of pressure with or without added heat. Although its use is frowned upon, hammering of locally-heated areas is sometimes used for straightening also. Cutting of plates and rewelding is used on occasion to remove distortion. This technique is perhaps the most expensive of all because of the time required.

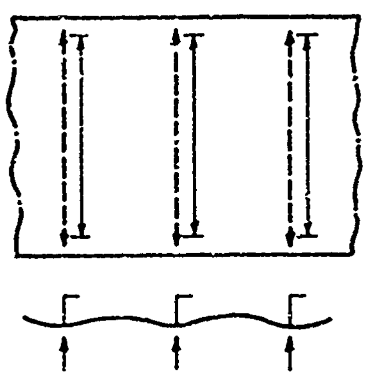
Flame straightening is well-established in the shipbuilding industry (and in other industries as well) as the most suitable method of removing distortion in welded assemblies of low- carbon steel. It is a relatively simple method and requires a minimum in equipment. However, flame straightening is not without its disadvantages. Despite its wide acceptance, flame straightening is an empirical process at best, and conscientious and well-trained workers and supervisory personnel are required for its effective application. Few material problems were encountered as long as low-



a. Spot Heating Panel



b. Line Heating Panel



c. Line Heating Back of Welds

Fig. 1. Heating Patterns For Flame Straightening

strength carbon steels were used in ship construction. However, the increasing use of high-strength low-alloy steels in the quench-and-tempered condition to obtain the required strength with savings in weight and cost, necessitates a reassessment of the flame straightening process and its effect on base-metal properties, since many of these steels are subject to property degradation by the incautious application of heat.

OBJECTIVES

A research program was initiated by the Ship Structure Committee in May, 1968 to determine the effect of flame straightening and mechanical straightening at elevated temperatures on the properties of steels used in ship fabrication.* The straightening of steel plates, pre-bent to produce small strains or slightly distorted by welding, was to be conducted at temperatures near 1200 F, a commonly-accepted flame straightening temperature. Steels with yield strengths of 40,000 to 100,000 psi were included in this work.

PROGRAM OUTLINE

The major effort of the experimental research program was directed toward a study of the effect of flame straightening and mechanical straightening on the properties of steels used in shipbuilding. Specifically, research was conducted to determine the effect of the following parameters on base-metal properties:

(1) Method of straightening
(2) Straightening temperature
(3) Amount of distortion
(4) Base-metal thickness

The schedule shown in Table 1 was established to meet these objectives. The same schedule was used to evaluate the effect of the straightening parameters on the properties of plates that were mechanically distorted or distorted during welding. A total of 45 unwelded and 45 welded plates were distorted, straightened, and evaluated by mechanical testing. The selection of the individual parameters shown in Table 1 are discussed in the following paragraphs:

(1) Amount of Distortion. Frequently, the amount of distortion encountered in shipbuilding is about 3 times the allowable unfairness between stiffeners. The amounts of distortion in the mechanically distorted plates, based on allowable unfairness data, were 1/2, 7/16, and 3/8 inch over a span of 18 inches for plates that were 3/8, 1/2, and 3/4-inch-thick respectively; these amounts of distortion or concavity were measured perpendicular to the centerline of the plate. For 1/2-inch-thick A517 Grade A plate, the effect of less

* The project number and title assigned by the Ship Structure Committee was SR-185 "Straightening Distorted Weldments".

Table 1. Schedule for Straightening Studies (Unwelded and Welded Test Specimens)

Code Number	Type of Steel	Plate Thickness, inch	Amount of Distortion, inch	Mechanical Straightening Temperature, F	Thermal Straightening Temperature, F	Number of Test Plates
1	A517, Grade A	1/2	None	-	-	2
2	Ditto	Ditto	7/16	1300	-	2
3	"	"	Ditto	1000	-	1
4	"	"	"	RT	-	1
5	"	"	9/64	1300	-	1
6	"	"	Ditto	RT	-	1
7	"	"	7/16	-	1300-1400	2
8	"	"	Ditto	-	1100-1200	1
9	A517, Grade A	3/8	None	-	-	2
10	Ditto	Ditto	1/2	1200	-	1
11	"	"	Ditto	RT	-	1
12	"	"	"	-	1300-1400	1
12a	"	"	"	-	1100-1200	1
13	A517, Grade A	3/4	None	-	-	2
14	Ditto	Ditto	3/8	1200	-	2
15	"	"	Ditto	RT	-	1
16	"	"	"	-	1300-1400	1
16a	"	"	"	-	1100-1200	1
17	A537	1/2	None	-	-	2
18	Ditto	Ditto	7/16	1200	-	2
19	"	"	Ditto	RT	-	1
20	"	"	"	-	1300-1400	1
20a	"	"	"	-	1100-1200	1
21	A441	1/2	None	-	-	2
22	Ditto	Ditto	7/16	1200	-	2
23	"	"	Ditto	RT	-	1
24	"	"	"	-	1300-1400	1
24a	"	"	"	-	1100-1200	1
25	ABS-B	1/2	None	-	-	2
26	Ditto	Ditto	7/16	1200	-	2
27	"	"	Ditto	RT	-	1
28	"	"	"	-	1300-1400	1
28a	"	"	"	-	1100-1200	1

distortion (9/64 inch) on base-metal properties was also studied.

(2) Straightening Temperature. The generally accepted temperature range for flame straightening distorted structual sections in shipyards is 1100-1200 F or when the plate glows "dull red". However, in practice temperature excursions well above and below this temperature range are likely. Thus, as shown in Table 1, temperatures on either side of the accepted range were selected for mechanical straightening; flame straightening was conducted in the accepted and above the accepted temperature range. A few distorted plates were mechanically straightened at room temperature also.

Following the removal of distortion, the effects of the straightening parameters were evaluated predominately by drop-weight tear tests.

Efforts were also directed toward (1) the fabrication and straightening of a structure that represented a ship structural component, and (2) a survey of new or novel methods to remove distortion in welded steel assemblies.*

MATERIALS

The base materials and welding electrodes are described in the following sections.

Base Metals

The steels which were investigated are typical of those used by the shipbuilding industry; included are steels that can be thermally straightened with little concern for property degradation as well as those with which care should be excercised when straightening is required. The types of steel, their strength levels, and their compositions are shown in Table 2 and Table 2a.

In selecting the plate thickness, two related factors were considered. First, distortion problems usually increase as the plate thickness in a structure decreases, because thinner plates deform easier. Second; material degradation becomes more severe as the plate thickness increases. In Figure 2, the effect of plate thickness on the relative seriousness of various types of distortion is shown. These curves indicate that:

(1) Buckling-type distortion decreases drastically as the plate thickness increases, and it almost disappears when the plate thickness exceeds about 3/8 inch.

(2) Distortion due to angular change in butt welds also decreases rapidly with increasing plate thickness; it is not a problem when the thickness exceeds about 1-inch.

(3) Distortion caused by the angular change in butt welds is usually not a major problem in shipbuilding unless proper welding procedures cannot be followed. This type of distortion exists regardless of plate thickness, although the amount of distortion decreases with increasing plate thickness.

(4) Material problems, on the other hand, become more serious as the plate thickness increases. It is well known that the notch toughness of steel decreases, or the transition temperature increases, as plate thickness increases. This is caused principally by varying degrees of hot reduction, finishing temperatures, cooling rates, etc. Also, notch toughness usually decreases as thickness increases because of the size effect (a geometric factor).

As shown in Table 2, most straightening experiments were conducted with 1/2-inch-thick plate; limited studies were made with 3/8 and 3/4-inch thick A517, Grade A plate. Mechanical tests were conducted to verify the specified properties of the respective steels; these data are presented in Table 3.

* The results of the survey are reported in APPENDIX A to this report.

Table 2. Steels Used in Thermal Straightening Studies

Type	Thickness, inch	Condition	Yield Strength (Range or min), psi	Tensile Strength (Range or min), psi
ABS-B	1/2	As rolled	40,000	58,000-70,000
A441	1/2	As rolled	50,000	70,000
A537	1/2	Normalized	50,000	70,000-90,000
A-517, Grade A	3/8, 1/2, 3/4	Quenched and tempered	100,000	115,000-135,000

Table 2a. Alloy Compositions

	Ladle Analysis, percent												
	C	Mn	Si	P	S	Cu	V	Ni	Cr	Mo	Al	Zr	B
ABS-B, 1/2 inch	0.18	0.93	--	0.008	0.030	--	--	--	--	--	--	--	--
A537, 1/2 inch	0.13	1.22	0.24	0.010	0.027	0.20	--	0.09	0.07	0.01	0.028	--	--
A441, 1/2 inch	0.19	1.17	--	0.009	0.022	0.23	0.07	--	--	--	--	--	--
A517, Grade A, 3/8 inch	0.19	0.88	0.60	0.009	0.024	--	--	--	0.67	0.20	--	0.13	0.0010
A517, Grade A, 1/2 inch	0.18	0.80	0.42	0.005	0.020	--	--	--	0.67	0.20	--	0.08	0.0009
A517, Grade A, 3/4 inch	0.18	0.88	0.55	0.008	0.026	--	--	--	0.69	0.22	--	0.06	0.0008

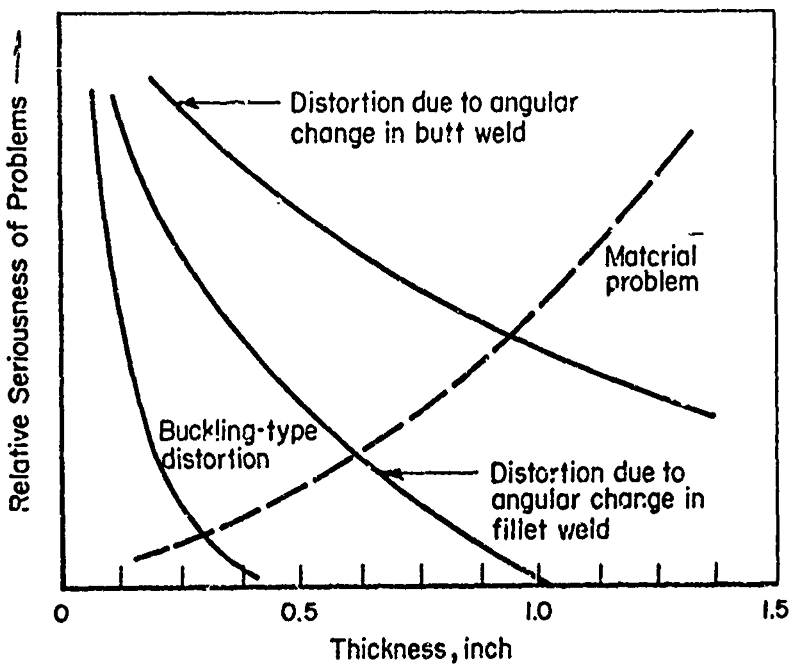


Fig. 2. Illustration of the Effects of Plate Thickness on the Relative Seriousness of Distortion Problems and Material Problems

The test plates used during this investigation had the following dimensions: 18-inches-wide by 24-inches-long (long dimension in the direction of rolling). The size of these plates was small in comparison with that of ship structural members, but they were large enough to demonstrate the effects of thermal and mechanical straightening procedures.

Welding Electrodes

The straightening studies were conducted with plate that was (1) distorted by mechanical pressing and (2) distorted by welding. Welded plates 18-inches-wide by 24-inches-long, were made by joining 2 plates, 9-inches-wide by 24-inches-long, with the shielded metal-arc or stick electrode process, using a vee-groove butt joint preparation. The following low-hydrogen electrodes were selected for welding:

E7018 for ABS-B Plate
E8018 for A441 Plate
E9018 for A537 plate
E11018 for A517, Grade A Plate

These electrodes were handled in accordance with sound welding procedures. After the electrode container was opened, the electrodes were placed in a drying oven until use; the temperature of the electrode oven was maintained at 250 ±25 F.

Table 3. Mechanical Properties of Base Metals

Steel Type	Thickness, inch	Specimen Orientation	0.2% Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation (2" G.L.), %	Charpy V-Notch Energy at Room Temperature, ft-lb
ABS-B	1/2	DR	39,800	63,900	41.0	138
	1/2	TDR	41,600	64,300	41.0	89.5
A441	1/2	DR	54,900	81,400	34.0	96
	1/2	TDR	59,700	81,200	30.0	28.5
A537	1/2	DR	50,500	70,700	39.0	86
	1/2	TDR	53,500	70,400	39.0	104
A-517, Grade A	3/8	DR	106,300	121,500	23.0	59.5
	3/8	TDR	109,000	123,000	21.0	38
	1/2	DR	115,300	124,300	22.0	75.5
	1/2	TDR	118,500	125,500	21.5	44
	3/4	DR	111,000	120,000	26.5	97
	3/4	TDR	109,300	119,800	22.0	45.5

Specimen Orientation: (1) DR: Specimen sectioned from plate in direction of rolling

(2) TDR: Specimen sectioned from plate transverse to direction of rolling.

Number of specimens: Two for each condition.

EXPERIMENTAL PROCEDURES

The procedures used for producing and removing distortion in plates, evaluation of straightening plates, and for distorting a structural weldment are presented in the following sections.

Production of Distorted Test Plates

Unwelded plates were bent in a 700-ton press to produce the amount of distortion shown in Table 1. A single die set shown in Figure 3 was used for bending; bending was done at room temperature. The ram of the press was allowed to contact the plate and deform it, mainly through its own weight; to avoid deformation along the plate centerline, additional pressure was not applied to the ram. The amount of distortion was controlled by a shim or "stop" positioned beneath the plate along its centerline. The amount of distortion was quite reproducible, and no difficulty was encountered in obtaining the desired distortion after the shim thickness was adjusted to compensate for springback.

Butt-welded test plates were also produced with the same amount of distortion produced in unwelded plates; i. e., (1) 7/16 inch for 1/2-inch-thick ABS-B, A441, A537, and A517, Grade A plate, (2) 1/2 inch for 3/8-inch-thick A517, Grade A plate, and (3) 3/8 inch for 3/4-inch-thick A517, Grade A plate.* Flat welded test plates were produced with all base metals also to evaluate the "no distortion" condition. During welding the amount of distortion was controlled by clamping the individual joint members to the work table with a shim of the proper thickness under each plate. The preparation of the welded plates is discussed in the following paragraphs.

(1) Joint Preparation. Plates, 9-inches-wide by 24-inches-long were flame cut with a 30 degree bevel along one edge. The joint surfaces were smoothed with a grinder and a 3/32-inch land was ground on each edge. As shown in Figure 4, two plates were butted together with a 3/32 to 1/8-inch root gap to form a test plate 18-inches-wide by 24-inches-long.

(2) Electrode Care. As mentioned previously, covered electrodes E7018, E8018, E9018 were used for welding. These are all low-hydrogen, iron-powder electrodes, and the moisture content of the electrodes must be maintained at a low level to insure crackfree welds, particularly with the high-strength, low-alloy steels. The electrodes were kept in a drying oven at 250 ±25 F until use. Electrodes E9018 and E11018 were used within one-half hour after their removal from the oven; the other electrodes were used within one hour after removal.

(3) Heat Input. The heat input for welding A517, Grade A steel must be carefully controlled to obtain optimum joint properties. The recommended heat inputs for welding various

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* Distortions of 9/64 inch were also produced in two 1/2-inch-thick plates of A517, Grade A steel as required by the schedule shown in Table 3.

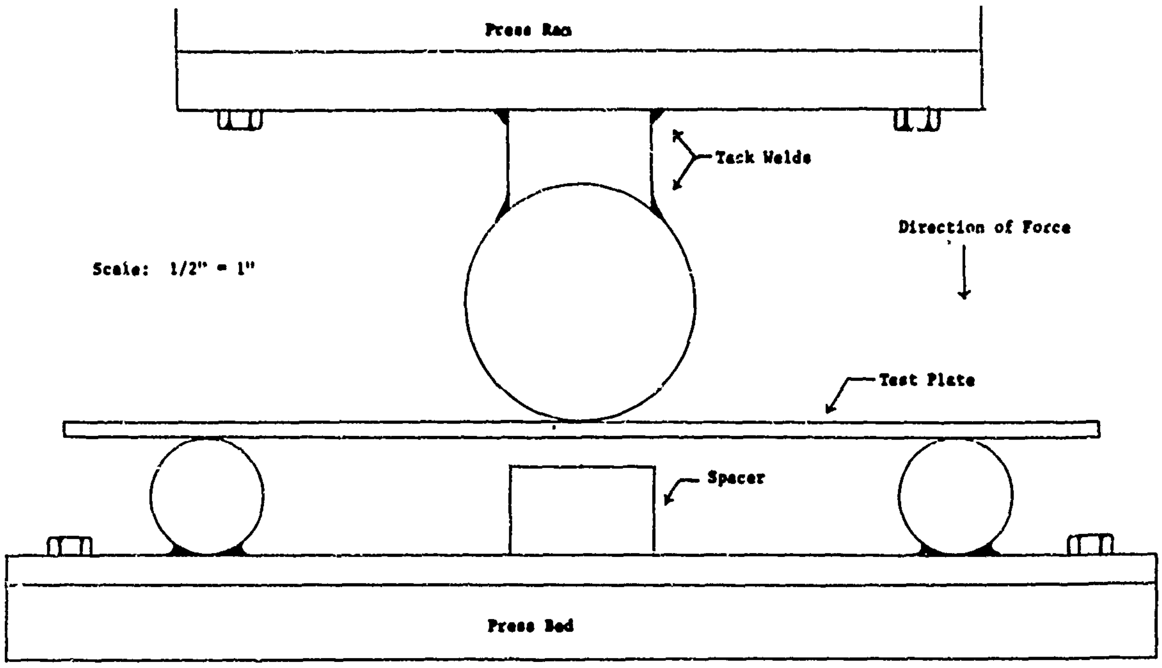

Fig. 3. Jigging for Mechanical Bending

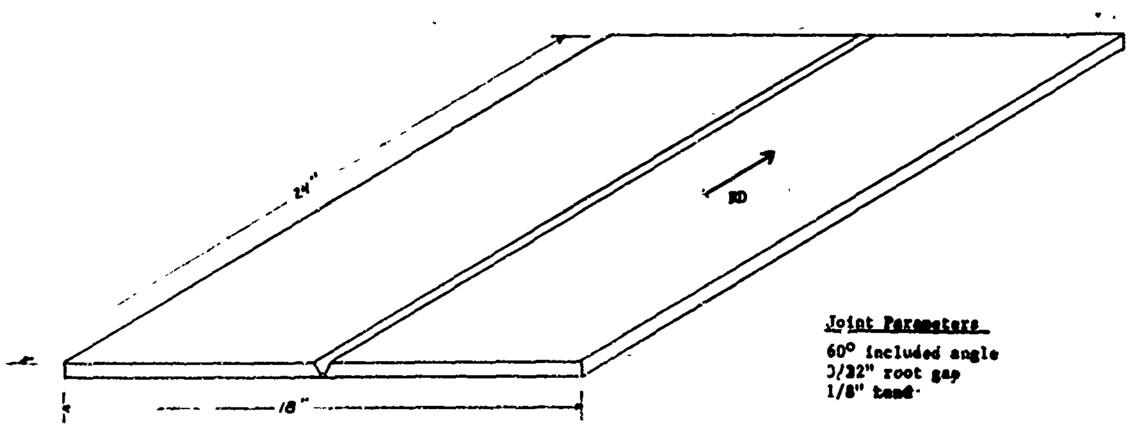

Fig. 4. Joint Design

thicknesses of A517, Grade A steel are:

41,000 joules/inch for 3/8-inch-thick-plate
52,000 joules/inch for 1/2-inch-thick-plate
98,000 joules/inch for 3/4-inch-thick-plate

These heat inputs were used for the first welding pass; they were reduced about 20 percent for succeeding passes. Neither preheat nor postheat was used.

The same heat inputs were used to weld the other grades of steel, although the properties of these steels are relatively insensitive to variation in heat input.

(4) Deposition Technique. To further maintain close control of the heat input, the stringer-bead technique was used for welding. Each weld bead was chipped and wire-brushed before the next bead was deposited. With 1/2-inch-thick plate, about 6 or 7 passes were required to fill the vee-groove. Then the plate was inverted and the root pass was ground back to sound metal before depositing the cover pass.

To produce plates with no distortion, the joint members were jigged and clamped as shown in Figure 5a. Flat plates were produeed with this jigging in 1/2-inch-thick ABS-B, A441, A537, and A517, Grade A steels and 3/4-inch-thick A517, Grade A steel. Less restraint was needed in the case of 3/8-inch-thick A517, Grade A steel; the clamps were loosened slightly to decrease the restraint.

The shims shown in Figures 5a were omitted during the production of welded plates with controlled amounts of distortion, and the joint members were merely clamped to the work table (Figure 5B). During welding the plates pulled up sufficently to produce the desired degree of distortion in 1/2-inch-thick ABS-B, A441, A537, and A517, Grade A steels and 3/4-inch-thick A517, Grade A steel. The clamping pressure was again reduced slightly when 3/8-inch thick A517, Grade A steel was welded.

The amount of distortion produced during welding was reproducible within experimental limits (i.e., within 1/32 to 1/16-inch of the desired amount). To simplify the straightening process, the weld reinforcement was removed from both sides of the joint by grinding. Post weld examination showed the plates to be free of cracks.

Straightening of Distorted Plates

Unwelded and welded ABS-B, A441, A537, and A517 test plates with controlled amounts of distortion were mechanically straightened and flame straightened. These studies are discussed in the following sections.

Mechanical Straightening

The mechanical straightening of distorted welded and unwelded plates was accomplished in a 700-ton hydraulic press using very simple jigging. The distorted plates were positioned (convex side up) on spacers, 1/2-inch-thick by 4-inches-wide, located along either edge of a flat plate; the flat

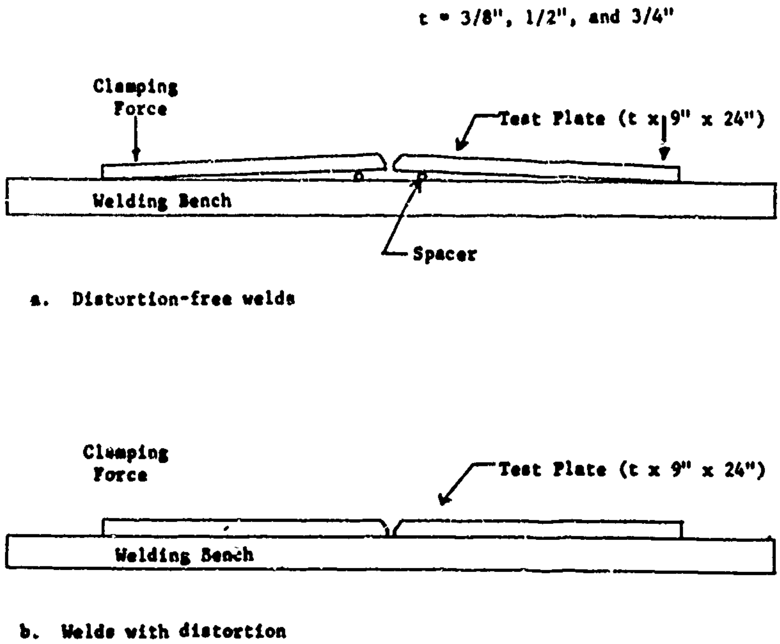

Fig. 5. Method of Controlling Distortion During Welding

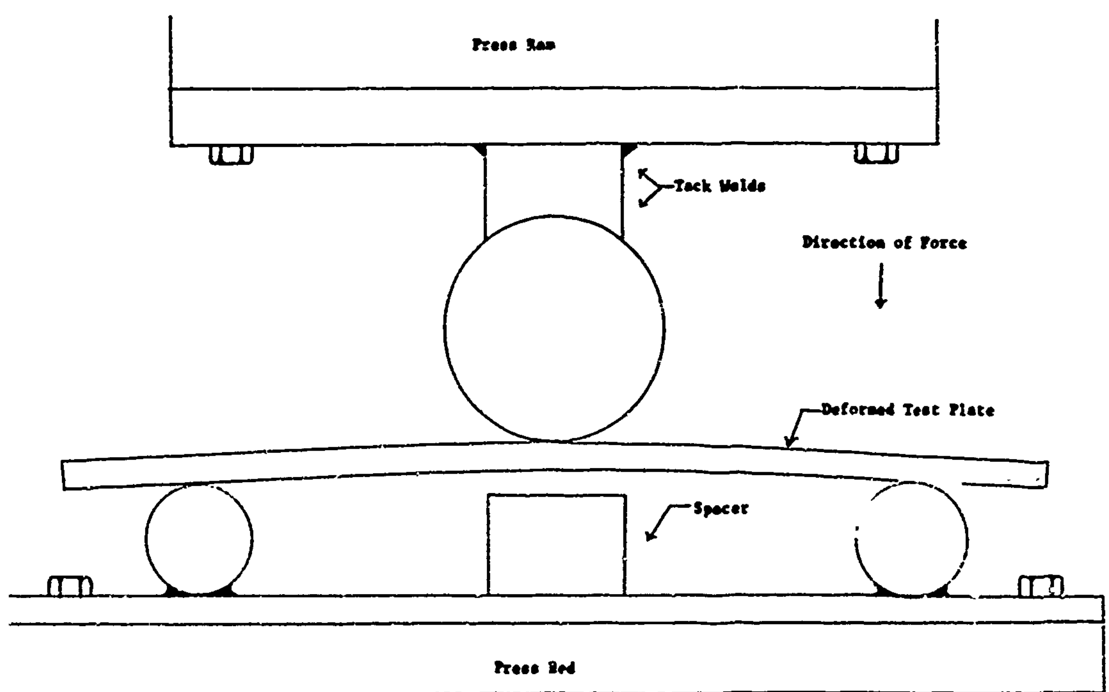

Fig. 6. Jigging for Mechanical Straightening

plate was fastened to the bed of the press (Figure 6). Straightening was done against shims located beneath the test-plate centerline. The shim thickness was adjusted for each type and thickness of plate to compensate for the minor amount of springback that occurred during straightening. To straighten the plates, the ram of the press was lowered until the bottom side of the test plate contacted the shim; the ram was held in position for a few seconds and then raised.

Mechanical straightening was also done at temperatures of 1000, 1200, and 1300 F as indicated in Table 1. The plates were heated individually to the specified temperature in a large gas-fired furnace, removed from the furnace, placed in a press, and straightened immediately. The surface temperature of the plates in the furnace was monitored with temperature- indicating pellets, and the plates were removed as soon as they reached the required temperature. The total heating time was 10 to 15 minutes; the plates were at the desired straightening temperature for one minute or less before removal for straightening. Since heating was accomplished mostly by convection, the surface temperature was a good indication of the plate temperature. As measured with temperature-indicating pencils, the temperature drop between the time the plates were removed from the furnace and the time straightening was completed was about 50 - 75 F.

Flame Straightening

Technique Development. While the techniques of flame straightening are well known, it was necessary to conduct preliminary studies to develop a technique that could be used to straighten the small, unrestrained plates used in this study. In contrast, the panels that are straightened aboard ship are several square feet in area and are restrained by welded stiffeners. To review briefly, shipyard flame straightening is accomplished in the following manner:

(1) Individual spots on the area to be straightened are heated with an oxyacetylene torch to a temperature of 1100-1200 F; then they are rapidly quenched with a water spray. The spots are 1 to 2-inches in diameter and are usually spaced on centers 6 to 8-inches apart. However, many spot patterns are used depending on the size of the panel to be straightened and the amount of distortion to be removed.

(2) Linear straightening is favored by many European and Japanese shipyards. The area to be straightened is heated with an oxyacetylene torch that is moved in a straight or curved linear direction; the torch is moved slowly to permit the area being heated to reach a temperature of 1100-1200 F. After the heating pass is completed, the panel is quenched in a water spray. It may be necessary to apply heat along several lines before a panel is straightened.

Both of these flame straightening methods were evaluated on the test plate during this study. The distorted test plates were positioned (convex side up) on a flat back-up plate. The plates were fastened with C-clamp along one edge to the back-up plate; the other edge of the test plate was free to move as straightening occurred. The results of these studies are discussed in the following paragraphs.

(1) Spot Heating. Attempts were made to straighten the test plate by heating discrete spots to temperatures of 1100-1200 F or 1300-1400 F; the spots were immediately quenched with a water spray after heating. The results of these studies were unsatisfactory, because the plates buckled as soon as they were quenched. Hence no quantitative studies were conducted on spot-heated panels.

(2) Linear Heating. Considerable success was achieved by linear heating along the plate centerline. Attempts were made first to heat the centerline area quickly to the selected straightening temperature. Although some straightening did occur during the heating cycle, much of the effect was lost when the plate was quenched. Additional studies indicated that satisfactory straightening could be obtained by applying heat more slowly along the plate centerline in repeated passes. Starting at one end of the plate, the centerline area was gradually heated as the torch moved along the plate; as soon as one heating pass was completed, another was started. After a few passes, the centerline area on the bottom of the plate reached the specified straightening temperature. Additional heating passes were made with the torch movement adjusted to maintain the desired temperature. As soon as the plate was straightened, it was quenched. No mechanical force was applied during straightening.

Plate Straightening

Unwelded and welded test plates were flame straightened in accordance with the procedures outlined in the previous section. Three thermocouples were embedded along the centerline in small holes drilled on the underside of the plate; the thermocouples were located in the middle and at 2-inches from each end of the plate. The thermocouples were connected to a recording potentiometer through a 3-pole switch, and three measurements were made during each heating pass.

The oxyacetylene torch was equipped with a No. 100 tip for straightening 1/2 and 3/4-inch-thick plate; a No. 90 tip was used to straighten 3/8-inch-thick plate. The following operating conditions were used: (1) oxygen-30 psi and acetylene -9 psi for 1/2 and 3/4-inch thick plate, and (2) oxygen-25 psi and acetylene -8 psi for 3/8-inch-thick plate.

The flame straightening data are summarized in Table 4 and are discussed in the following paragraphs:

(1) The distortion removal in both welded and unwelded plates required approximately the same number of passes.

(2) The 3/8-inch-thick A517, Grade A plate required more passes to straighten than the 1/2 and 3/4-inch thick A517 plate. The thin plate had a tendency to bow in the opposite direction when it was quenched after straightening. In some instances, straightening produced a compound curvature in the plate.

(3) In most cases, fewer passes were required for straightening in the 1300-1400 F range than in the 1100-1200 F range.

Table 4. Flame Straightening Studies

Plate Number	Steel	Thickness, inch	Amount of Distortion, in.	Plate Condition	Straightening Temperature, F	Number of Heating Passes	Heating Time (above 1050 F), min.	Total Heating Time, min.*	Remarks
10817	A517, Grade A	1/2	7/16	Unwelded	1300-1500	9	4.0	20	Flat Plate
10818	A517, Grade A	1/2	7/16	Welded	1300-1400	8	3.3	18	Flat Plate
10815	A517, Grade A	1/2	7/16	Welded	1200-1400	7	2.5	15	Almost flat-very slight bow on opposite side
10823	A517, Grade A	1/2	7/16	Unwelded	1100-1200	5	2.0	20	Flat Plate
10816	A517, Grade A	1/2	7/16	Welded	1100-1200	4	1.0	10	Flat Plate
484	A517, Grade A	3/8	1/2	Unwelded	1300-1400	23	5.0	50	Plate bowed on opposite side-straightened twice
1383	A517, Grade A	3/8	1/2	Welded	1300-1400	10	5.0	25	Flattened during heating-bowed after cooling
485	A517, Grade A	3/8	1/2	Unwelded	1100-1200	9	2.8	22	Flattened-bowed on opposite side after cooling
13	A517, Grade A	3/8	1/2	Welded	1100-1200	12	3.3	30	Flattened-bowed on opposite side after cooling
1282	A517, Grade A	3/4	3/8	Welded	1300-1400	6	2.0	20	Flat Plate
982	A517, Grade A	3/4	3/8	Unwelded	1100-1200	6	1.8	22	Flat Plate
1285	A517, Grade A	3/4	3/8	Welded	1100-1200	6	1.7	20	Flat Plate
384	A537	1/2	7/16	Unwelded	1300-1400	13	6.6	25	Flat Plate
A537	A537	1/2	7/16	Welded	1300-1400	13	6.0	25	Flat Plate
385	A537	1/2	7/16	Unwelded	1100-1200	23	8.0	42	Flat Plate-straightened twice
387	A537	1/2	7/16	Welded	1100-1200	27	7.5	52	Flat plate-straightened twice
185	A441	1/2	7/16	Unwelded	1300-1400	12	3.3	22	Flat plate
986	A441	1/2	7/16	Welded	1300-1400	10	3.3	22	Flat plate
186	A441	1/2	7/16	Unwelded	1100-1200	20	8.0	32	Flat plate-straightened twice
987	A441	1/2	7/16	Welded	1100-1200	27	5.0	32	Flat plate-straightened twice
282	ABS-B	1/2	7/16	Unwelded	1300-1400	--	---	--	Difficult to straighten
789	ABS-B	1/2	7/16	Welded	1300-1400	18	4.5	40	Difficult to straighten
8814	ABS-B	1/2	7/16	Welded	1100-1200	12	3.9	25	Flat plate

* Heating time was recorded from start of heating until quenching occurred.

Evaluation of Straightened Plates

The steels used in ship fabrication must posses a suitable degree of notch toughness and weldability in addition to conventional mechanical properties such as tensile strength, yield strength, and elongation. Adequate notch toughness is needed to avoid brittle fracture in welded structures. In the past 35 years many research programs on various aspects of brittle fracture in welded structures and the notch toughness of steels have been conducted. Straightening may produce a reduction in the notch toughness and mechanical properties of the base metal since plastic deformation occurs during either mechanical or thermal straightening processes. The elevated temperatures required for flame straightening can also cause degradation in material properties. Because of the importance of notch toughness to the designer and builder of ships and because of the close relationship of notch toughness and brittle fracture, this parameter was selected as the criteria in evaluating the effects of straightening treatments on base-metal properties.

Many tests have been designed and used to evaluate the notch toughness of steel and the brittle fracture characteristics of welded structures. These tests have been discussed in considerable detail by Masubuchi, Martin, and Monroe in Ship Structure Committee Report SSC-169.[1] The Charpy V-notch impact test with standard-sized specimens is the most commonly used notch-toughness test. However, because the Charpy impact test evaluates the notch toughness of a very small area, there has been a trend in recent years to use tests conducted with relatively large specimens to evaluate the notch toughness of the steel plates used in ship hull construction. The NRL Drop-Weight Test (developed at the U. S. Naval Research Laboratory) and the Drop-Weight Tear Test (developed more recently by the Naval Research Laboratory and Battelle) are typical of these tests.[2-4]

(1) The NRL Drop-Weight Test can be used to determine the nil-ductility transition temperature (NDT) of a material. Below the NDT temperature the steel does not deform prior to fracture, and fracturing occurs immediately upon reaching the yield point. The test is conducted with a rectangular flat-plate specimen containing a crack starter formed by a notched, brittle, hard-facing weld bead. Specimens are tested over a range of temperatures.

(2) The Drop-Weight Tear Test (DWTT) is conducted in much the same manner as a Charpy V-notch test, the major difference being the size and shape of the specimen. The specimen shown in Figure 7, is used at Battelle; the specimen used at the Naval Research Laboratory is similar to that shown in Figure 7, but has slightly different dimensions and a different method of providing a brittle crack path. The DWTT is conducted on a large pendulum-type impact machine (essentially an over-sized Charpy machine) over a wide temperature range. This test provides much of the same type of data generated by the NRL Drop-Weight Test.

The DWTT was selected to study the effects of mechanical and flame straightening on the properties of welded and unwelded ship steels.

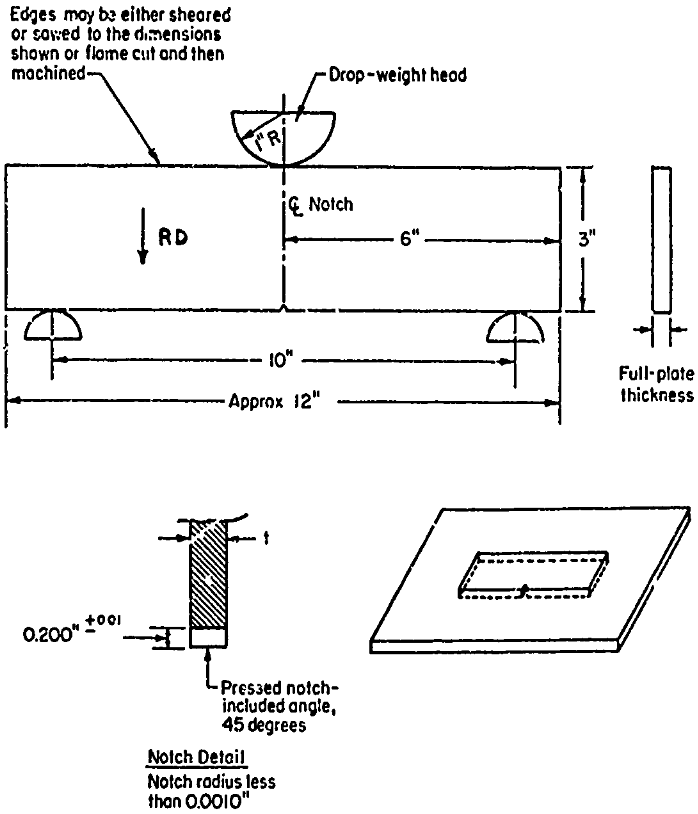

Fig. 7. Drop-Weight Tear-Test Specimen Employed at Battelle Memorial Institute[4]

Drop-Weight Tear Testa

The specimens for the DWTT were prepared in accordance with the provisions of Figure 7. Individual specimens were sheared to size and edge-notched with a knife-like tool; the centerline of the specimen corresponded to that of the test panel. Before notching, the edges of the specimens were ground to remove the imperfections caused by the shearing operation and to facilitate notch location. The notch was located in the center of the unwelded specimens. Welded specimens were notched at the edge of the heat-affected zone; the edges of the specimens were etched to define the location for this notch.

The drop-weight tear tests were conducted in accordance with accepted procedures over a temperature range that was appropriate for the type of steel being investigated. A series of 8 or 9 control specimens were tested to establish base line data for each type and thickness of steel. The control specimens were sectioned from (1) as-received plate and (2) plate welded with little or no distortion. The energy absorption prior to fracture and the mode of fracture were recorded for each specimen, and curves of energy absorption and percent shear fracture were plotted. Then, 5 DWTT specimens representing each type and thickness of steel that was distorted and straightened were tested. Energy absorption and percent shear fracture curves were plotted from these data also. The data are presented in Appendix B of this report.

To facilitate discussing the experimental data, the 50 percent shear area transition temperature was selected as the major criteria in assessing the effects of the straightening parameters on base metal properties; the energy absorption and percent shear fracture curves were considered also. Various methods can be used to determine this temperature; in this investigation, the temperature corresponding to 50 percent shear area was used. A change of 20 F in the transition temperature is considered significant in this test.[5]

Hardness Tests

Hardness testing was selected to assess the effects of the straightening treatments on the mechanical properties of the test plates. Consideration was also given to the use of standard tensile tests for this purpose but these were rejected. It was reasoned that the tensile tests would provide data that was possibly misleading since the test section would contain a region of gradation in properties. Consequently, interpretation of the significance of tensile tests was not expected to be possible. Conversion of hardness readings to tensile strength was expected to provide more meaningful data.

The hardness measurements were taken using a Rockwell A indention on the surface of half of a broken DWTT specimen representing each treatment. The surfaces were ground prior to taking the hardness readings to avoid spurious results, yet it was difficult to obtain absolute values. The comparison tabulated below indicates the differences observed between readings from the DWTT measurements and measurements made on mounted and polished cross sections.

Comparison of Hardness Values

Material, All As Received	Hardness, R_A DWTT Specimen	Cross Section
ABS-B	39.9	46.5
A441	46.0	53
A537	46.4	45
A517, Grade F	57.9	62.5

Despite the uncertainty of the absolute hardness values, it is believed that useful comparisons can be made using the values measured on the DWTT specimens. All hardness values reported are an average of at least 3 readings. The hardness data appears in Table B-3.

Fabrication and Straightening of Structural Weldment

Limited studies were made to fabricate and flame straighten a structural weldment. The structure shown in Figure 8 was fabricated from 1/2-inch-thick A517, Grade A plate using normal fillet welding procedures.

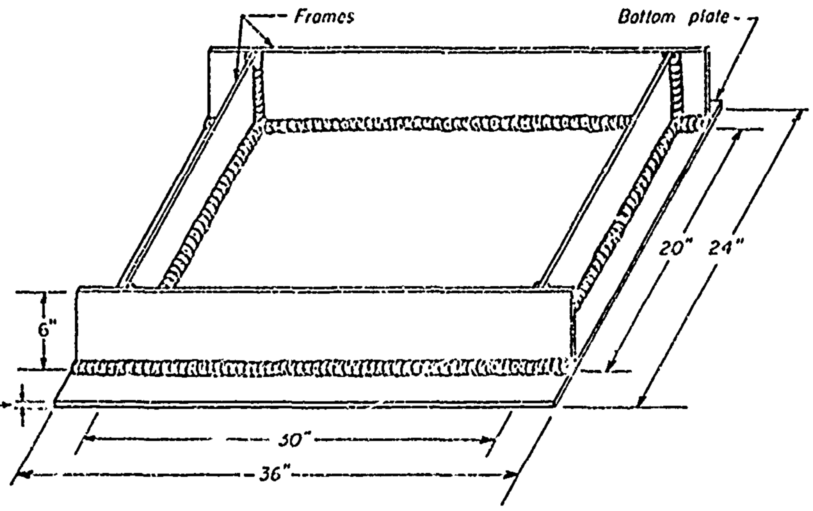

Fig. 8. Structural Weldment

It was expected that the fillet welds between the framing members and the bottom plate would produce measurable distortion in the bottom plate. However, no significant amount of distortion occurred and flame straightening studies were therefore not conducted.

In future work, it is planned to weld the test plate into an I-beam frame rather than use this panel. Distortion can be administered either by overwelding in joining the plate to the I beams or deforming the plate mechanically before welding.

RESULTS

The results of the Drop Weight Tear tests are presented in Table 5. As stated previously, a change of 20 F or more in the transition temperature is considered to be significant.

Reference Plates

Although the tensile strength of A517, Grade A as converted from hardness measurements was low, the tensile strength as measured directly was within the ASTM specifications. Consequently, the hardness values shown in Table B-3 must be used qualitatively to show relative changes and should not be used quantitatively.

There is no ASTM requirement on transition temperature with which to compare the values obtained by DWTT. There was no significant rise in transition temperature due to welding for any alloy except the 3/8-inch A517, Grade A plate; however, the transition temperatures measured after welding both the 1/2-inch and 3/8-inch A517, Grade A plates were comparable.

Cold Straightening

Significant changes in transition temperatures were found for both welded and unwelded plates of A537 and ABS-B; since the measured

Table 5. Effect of Mechanical and Flame Straightening Upon the Transition Temperature of Test Plates

Code Number	Alloy	Plate Thickness, inch	Straightening Temperature, F	Transition Temperature,(a) F Unwelded Plate	Transition Temperature,(a) F Welded Plate
			Reference Plates (No Straightening)		
1	A517, Grade A	1/2	--	-55	-40
9	A517, Grade A	3/8	--	-80	-44
17	A537	1/2	--	- 5	-10
21	A441	1/2	--	+30	+40
25	ABS-B	1/2	--	+52	+60
			Cold Straightened		
4	A517, Grade A	1/2	RT	-55	-53
6	Ditto	1/2	RT	-68	-43
11	"	3/8	RT	-76	-55
19	A537	1/2	RT	+20	+20
23	A441	1/2	RT	+46	+38
27	ABS-B	1/2	RT	+85	+80
			Mechanically Straightened at Elevated Temperature		
2	A517, Grade A	1/2	1300	-120	-45
3	Ditto	1/2	1000	- 70	-40
5	"	1/2	1300	- 77	-46
10	"	3/8	1200	- 80	-35
18	A537	1/2	1200	- 5	- 8
22	A441	1/2	1200	+ 52	+40
26	ABS-B	1/2	1200	+ 63	+60
			Flame Straightened		
7	A517, Grade A	1/2	1300-1400	+ 53	+46
8	Ditto	1/2	1100-1200	+ 20	-15
12	"	3/8	1300-1400	+125	+70
12a	"	3/8	1100-1200	+ 33	+40
20	A537	1/2	1300-1400	+ 23	+ 5
20a	A537	1/2	1100-1200	+ 20	+ 2
24	A441	1/2	1300-1400	+ 42	+37
24a	A441	1/2	1100-1200	+ 46	(b)
28	ABS-B	1/2	1300-1400	+ 70	+65
28a	ABS-B	1/2	1100-1200	(b)	+40

(a) The transition temperature is that at which the fracture contains 50 pct shear area.

(b) Not determined.

increases were similar for both welded and unwelded plates, there is no additional degradation in the heat-affected zone beyond that caused by the cold straightening. The response of the A517, Grade A plates to cold straightening was comparable irrespective of whether the initial deformation was 7/16 inch (Code 4) or 9/64 inch (Code 6). No appreciable change in hardness was observed for any alloy as a result of cold straightening.

Mechanical Straightening at Elevated Temperatures

The only steel to show a significant increase in transition temperature due to mechanical straightening at elevated temperatures was the unwelded plate of A441 (Code 22). An anomalous decrease in transition temperature was observed after mechanically straightening the 1/2-inch plate of A517, Grade A at 1300 F. Although mechanical straightening at elevated temperatures is in general not detrimental to toughness, it does cause reduction in strength of both A537 and A517, Grade A.

Flame Straightening

All plates of A517, Grade A, both welded and unwelded, underwent a significant increase in transition temperature as a result of flame straightening. This increase was larger when the flame straightening was performed in the temperature range between 1300 and 1400 F than in the range between 1100 and 1200 F. The unwelded A537 plates underwent a significant increase in transition temperature after flame straightening in both of these temperature ranges, but the welded plates of the same steel were unaffected. The toughness of both the welded and the unwelded plates of A441 and ABS-B was unaffected by flame straightening. The particularly high transition temperature for the unwelded plate of 3/8-inch A517, Grade A is due to a longer time at temperature since this plate was straightened twice.

The strength of the welded 1/2-inch plate of A517, Grade A was reduced considerably by flame straightening between 1300 and 1400 F, but not by flame straightening between 1100 and 1200 F. None of the other plates showed significant changes in strength due to flame straightening in either temperature range.

Discussion

Results of this study demonstrated that an expected adverse effect of straightening operations on material properties does occur with certain combinations of materials and treatments. Although it is clear that some treatments (flame straightening of A517 Grade A at the temperatures studied) should not be permitted, the analysis of other treatments is not as clear cut. A major difficulty in assessing the significance of straightening treatments is the lack of established notch toughness criteria for many grades of ship steel. For example, with the A537 steel significant differences in transition temperature were measured (from -5 F to +23 F). However, since there is no set toughness required for this steel one cannot readily say that a +23 F transition temperature represents a degrading condition.

The results indicate that the widespread use of flame straightening on ABS-B steel is an acceptable procedure. This is also true for the A441 steel. Flame straightening of A537 should be examined with care to insure that the resulting loss in toughness does not lead to trouble. Flame straightening of A517 Grade A should not be done, unless detailed procedures that avoid the degrading effects observed in this work are developed.

As expected, the effect of the straightening parameters on base-metal properties was most noticeable when the quenched-and-tempered A517, Grade A steel was flame straightened. The transition temperature increased markedly, and the curves for energy absorption and percent shear fracture were shifted in the direction of increased temperatures; the energy absorbed at temperatures above that at which transition occurred decreased also. These indications of reduced notch toughness were most pronounced when flame straightening was done at temperatures over 1200 F. However, even the widely accepted flame straightening temperature range or 1100-1200 F may be too high for some quenched-and-tempered steels depending on their transformation characteristics.

The time required for flame straightening also had an adverse effect on the notch-toughness properties of A517. Then, if problems are experienced in straightening a distorted structure made from this or a similar steel and repeated applications of heat are required to remove the distortion, a reduction in base-metal properties can be expected, even if straightening is conducted under otherwise normally accepted conditions.

SUMMARY

The results of the experimental program are summarized below:

(1) Mechanical straightening of all plates at all temperatures was accomplished readily.

(2) Flame straightening by spot heating could not be used to straighten the unrestrained test plates used in this program. Line heating was used successfully to accomplish the desired straightening.

(3) Table 6 contains the net numerical change in transition temperature for each of the steels investigated. Where more than one plate was straightened under identical conditions, an average increase is shown. The following straightening treatments produced a significant change in transition temperature:

a. Flame straightening of A517, Grade A and A537.

b. Mechanical straightening at room temperature of A537 and ABS-B; mechanical straightening at 1200 F of A441.

(4) The transition temperatures of all the welded plates were generally comparable to companion unwelded plate given a similar treatment. The only exception to this behavior was the thinnest A517 Grade A, where a consistently higher transition temperature was noted in the as-welded and mechanically straightened welded plate.

(5) Mechanical straightening at elevated temperatures causes a considerable reduction in strength in the heat-treated materials (A517, Grade A and A537) although this treatment is not detrimental to toughness.

Table 6. Increase in Transition Temperature Due to Straightening

Alloy	Straightening Temperature, F	Change in Transition Temperature, F — Unwelded Plate	Change in Transition Temperature, F — Welded Plate
	Cold Straightened		
A517, Grade A; 1/2"	RT	- 6	- 8
A517, Grade A; 3/8"	RT	+ 4	-11
A537; 1/2"	RT	+25	+30
A441; 1/2"	RT	+16	- 2
ABS-B; 1/2"	RT	+33	+20
	Mechanically Straightened		
A517, Grade A; 1/2"	1300	-44	- 5
A517, Grade A; 1/2"	1000	-15	0
A517, Grade A; 3/8"	1200	0	+ 9
A537; 1/2"	1200	0	+ 2
A441; 1/2"	1200	+22	0
ABS-B; 1/2"	1200	+11	0
	Flame Straightened		
A517, Grade A; 1/2"	1300-1400	+108	+ 86
A517, Grade A; 1/2"	1100-1200	+ 75	+ 25
A517, Grade A; 3/8"	1300-1400	+205	+114
A517, Grade A; 3/8"	1100-1200	+113	+ 84
A537; 1/2"	1300-1400	+ 28	+ 15
A537; 1/2"	1100-1200	+ 25	+ 12
A441; 1/2"	1300-1400	+ 12	- 3
A441; 1/2"	1100-1200	+ 16	*
ABS-B; 1/2"	1300-1400	+ 18	+ 5
ABS-B; 1/2"	1100-1200	*	- 20

* Not determined.

(6) Specific comment is warranted for several tests as indicated below:

a. The very low transition temperature (-120 F) for the Code 2 unwelded plate is not explainable.

b. The lower than expected transition temperature for the Code 8 welded plate is believed to reflect a shorter time at temperature (about 1/2 the average time required).

c. Similarly the high value for Code 12, unwelded reflects a longer time at temperature since this plate was straightened twice.

Special Notes for Fabricators

The information developed in this program has established a number of points that can be of immediate assistance to ship structure fabricators. Some of this information is not necessarily new, but merely verifies previous ideas. The most important points of interest and use to fabricators are summarized below.

(1) Flame straightening A517, Grade A above 1200 F should never be permitted.

(2) Flame straightening of ABS-B and A441 is permissible at temperatures up to 1400 F.

(3) Both weldments and prime plate of ABS-B and A441 can be flame straightened by identical producers.

SUGGESTIONS FOR FUTURE RESEARCH

In the course of the current program it was apparent that this research would not produce all of the data desired by the Ship Structure Committee, because additional study is needed to cover many aspects of straightening not included in this program. In the present study (1) mechanical straightening was done at room temperature and at two temperatures near or in the conventional flame straightening temperature range, and (2) flame straightening was done at temperatures above and below the lower critical temperature of the steel. The effect of these temperatures on base-metal properties was assessed by drop-weight tear tests. However, in the case of flame straightening, it is important to consider what happens to the properties of some steels in areas slightly removed from the spot being heated. While flame straightening may be carried out in accordance with accepted practice, with some steels (particularly the quenched-and-tempered low-alloy, high-strength steels) microstructures with undesirable effects on the notch toughness of the steel may be formed at some distance away from the heat spot. A notch or discontinuity in this unsuspected area may lead to fracture.

The effects of the flame straightening temperature on base-metal properties are largely governed by the transformation behavior of the steel. Even though two high-strength quenched-and-tempered steels may have similar composition and properties, the differences in the transformation characteristics (such as those that exist between A517, Grade A, Grade B, and Grade F) can produce different results in the amount of material degradation. It is apparent that further research must emphasize these steels as plain carbon steels are not affected by flame straightening.

Additional research is therefore recommended as follows:

(1) Spot heating should be performed upon plates restrained on all four sides.

(2) As the straightening produced by line heating tests occurred due to the flame alone, the quench is unimportant in straightening. It should therefore be determined whether the quench is harmful or beneficial to material properties.

(3) Additional grades of A517 should be studied.

(4) Stiffened panels should be distorted by depositing an excess of filler metal and subsequently flame straightened.

(5) The impact strength in straightened plate of weld metal and base plate removed from the heat-affected zone should be studied by altering the position of the notch.

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APPENDIX A

SURVEY OF OTHER STRAIGHTENING METHODS

Despite the many advances that have been made in methods of fabricating ship structural sections while minimizing the amount of distortion that occurs in them, some distortion does occur, and it must be removed when it exceeds acceptance standards. However, the development of straightening techniques has not kept pace with other developments in the shipbuilding industry. While there is considerable disagreement concerning the merits of various flame straightening techniques (i.e., spot versus line or streak heating), the effectiveness of this process in removing unwanted distortion in welded steel structures has been long recognized by its almost universal acceptance by ship builders in spite of its slowness, its costliness in terms of labor, and its potentially harmful effects on base metal properties. However, the capital cost of the required equipment is low and operators can be readily trained.

The results produced by this investigation indicate that the base metal properties can indeed be adversely affected by the heat developed during flame straightening; this is particularly the case when the low-alloy, high-strength steels being used or being considered for use in ship fabrication are straightened. Heating these steels to temperatures in excess of the recommended range of 1100-1200 F decreases their impact strength and increases the temperature at which the transition from ductile to brittle fracture occurs. Since flame straightening temperatures are estimated visually, it is quite likely that the base metal will be inadvertently heated above 1200 F on some occasions. Heating to such temperatures will upset the mill heat treatment of the quenched and tempered steels at the very least; if these steels are heated above the lower cr[illegible]cal temperature, microstructures with reduced notch toughness can be produ[illegible].

Thus, there is a demonstrated need for new and improved techniques to remove distortion from welded steel structures without affecting the base metal properties. The methods to be discussed are broadly categorized as those involving heat and those in which high-energy-rate deformation plays a major role.

Thermal Straightening

As mentioned in the previous section, flame straightening has been used most successfully to remove excess distortion; however, the heat developed by this process cannot be readily controlled. Two processes whose heat output can be controlled by sensing the temperature to which a base plate is heated for straightening are discussed below:

Plasma Arc Heating

The plasma arc has been under development for the past decade as a technique for (1) welding, (2) metal cutting, and (3) spraying metallic and non-metallic powders. Because of its high arc temperature, the plasma arc has also been used as a source of intense heat for chemical and for high-temperature environmental studies. Since base metal properties are affected not only by the maximum temperature to which the base metal is heated, but also by the duration of the heating cycle, plasma arc heating appears to offer several advantages over conventional flame straightening.

For straightening purposes the plasma arc should be operated in the non-transferred mode. In this mode the arc is established between the torch electrode and nozzle, and the heat energy is conducted to the workpiece by the intensely heated plasma gases. The transferred mode of operation in which the arc is established between the electrode and the workpiece appears to be unsuitable for straightening, because of arc strikes and areas of partial melting.

The plasma arc would be useful for spot heating and for heating along straight or curved lines. The heating capabilities of such equipment permit extremely rapid heating cycles when compared to those that can be obtained with the oxyacetylene flame. To regulate the diameter of the heated spot or the width of the heated line, the torch could be positioned a predetermined distance from the workpiece by appropriate fixturing.

The heating rate of the plasma-arc torch could be readily controlled by regulating the power input and the flow rate of the plasma gases. Similarly, heating could be discontinued by (1) sensing the temperature to which the base plate has been heated, and (2) feeding this signal to the "on-off" switching circuitry by conventional means. The temperature-sensing device could be located on the back or front of the plate to be straightened. In this manner it would be possible to automatically control the temperature to which a spot or line on the base plate is heated.

On the debit side, the capital expenditures for plasma-arc equipment are much greater than those for conventional flame straightening equipment; to a degree, these costs can be balanced by a higher productivity rate and the assurance that overheating during straightening will not occur.

Induction Heating

Induction heating appears to offer some of the advantages of plasma-arc heating such as (1) a controlled heating rate, and (2) the possibility of preventing overheating by means of appropriate electrical circuitry. However, the efficiency of induction heating is determined by the amount of energy that can be transferred to the workpiece. In low- and medium-frequency induction heating, considerable research would have to be conducted to design and fabricate coils that would transfer maximum energy to the workpiece. While fewer problems of this nature might be encountered with high-frequency induction heating, this process does not appear to be suitable because only the base-plate surface would be heated due to the skin effect.

As in the case of plasma-arc equipment, the costs for induction heating units are high in comparison with those for conventional flame straightening equipment.

High-Energy-Rate Processes

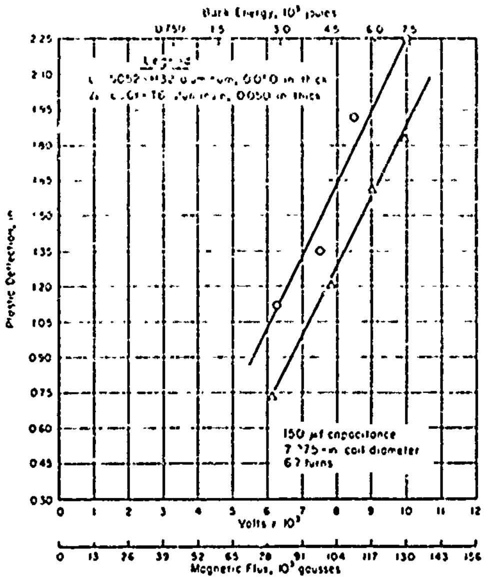
In recent years a number of high-energy-rate processes have been designed and developed for use in forming components for the aerospace industry-components that would be difficult, impossible, or too costly to form by conventional metalworking methods. A major attribute associated with these processes is that metals can be formed cold. Since the removal of distortion is essentially a forming operation, the high-energy-rate processes are attractive for straightening, particularly if heating of the base metal can be entirely eliminated.

Of the currently available processes those using high-intensity magnetic fields for forming appear to be candidates for straightening distorted structural sections aboard ship. For example, high-energy-rate presses have been developed for forming operations, but presses are generally unsatisfactory for straightening unless the parts can be moved and the press is large enough to handle them. Similarly, explosive techniques have been developed for forming, cladding, and joining operations. However special facilities are required for forming -- facilities that would be difficult to provide aboard ship so that straightening could be done conveniently and safely. Research has been undertaken at Republic Aviation Corporation on the development of electro-hydraulic forming equipment, and considerable success has been obtained in the production of domed components.(1) With this process high-voltage energy stored in a capacitor bank is discharged instantaneously between work electrodes located in a liquid medium and a pressure wave is produced; the energy contained in this wave is available for forming purposes. Again, it is difficult to imagine how this process could be used in its present form for the straightening of ship and deck structural members in view of the process requirements. Thus, this discussion is concerned only with the possible use of magnetic-pulse forming.

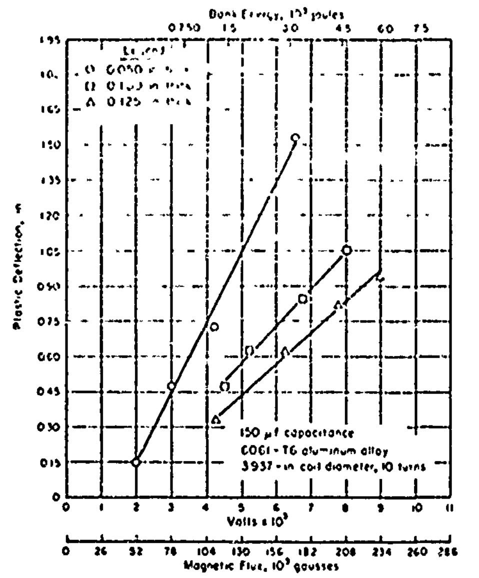
Magnetic-pulse forming is somewhat similar to the electro-hydraulic process discussed immediately above in that the energy required for forming is stored in a capacitor bank. However, in this instance, the energy is discharged through a suitable switching circuit into a coil where a high-intensity pulsed or transient magnetic field is created. In principle, the current in the coil produces a magnetic field which causes an eddy current to flow in the workpiece which is located in close proximity to the coil. The eddy current then provides an induced field that interacts with the primary coil to create a high magnetic pressure between the workpiece and the coil pressure that is available for metal forming purposes.

This principle has been used in the development of the so-called "electromagnetic hammer". The electromagnetic hammer has been investigated by Republic Aviation Corporation (2) and by Advanced Kinetics, Incorporated(3) in programs initiated by the National Aeronautics and Space Administration (NASA); the results of these studies have been summarized in a NASA report that was published in December, 1965.(4) This equipment was developed to remove the distortion produced by welding in space vehicle structural sections.

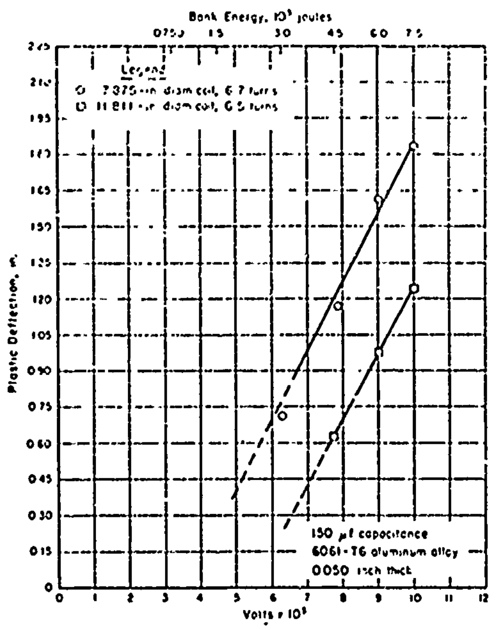
The electromagnetic hammer (so-called because it can be used in place of a hammer) consists of the following major components: (1) a power source, (2) a capacitor bank for storing energy, (3) switches, (4) transmission lines, and (5) a magnetic coil. Most of the research has been concerned with the development of suitable magnetic coils for this equipment. A typical coil consists of a spirally wound and insulated



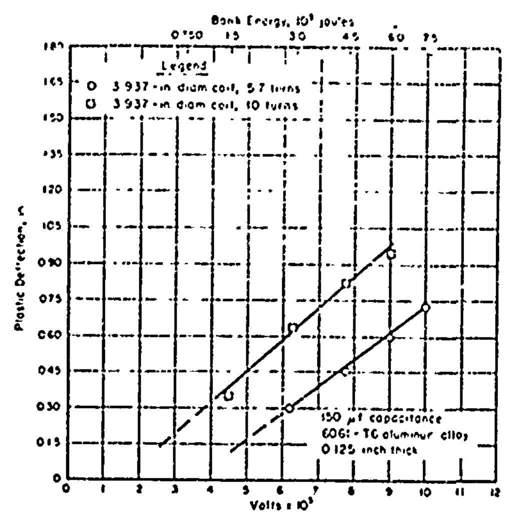
a. —Plastic deflection at the center of free-formed aluminum sheets produced by electromagnetic hammers operated at various energy levels (ref. 5).



b. —Effect of discharge energy on the plastic deformation produced by electromagnetic hammers on free-formed aluminum sheets of three different thicknesses (ref. 5).



c. —Plastic deflection at the center of free-formed aluminum sheets for various energy levels discharged through coils of different diameters (ref. 5).



d. —Plastic deflection and energy for two coils of the same diameter but different number of turns (ref. 5).

Fig. A1. Effect of Coil Design Parameters and Energy Level on the Deflection Produced with the Electromagnetic Hammer[4] heavy conductor that is encapsulated in an epoxy resin. The coil is mounted in a holder that is used to position the coil with respect to the workpiece; the holder is usually designed to absorb the recoil from the hammering operation.

The effects of various parameters on the amount of plastic deformation at the center of free-formed aluminum sheet are shown in Figures 1a-1d. These data indicate that (1) an increase in the coil diameter, the number of turns, and the amount of available energy results in an increase in the amount of deflection, and (2) the amount of deflection decreases with an increase in the material strength, thickness, and resistance and with an increase in the coil-to-work piece distance.

The material to be deformed must be considered part of the magnetic circuit, and the material conductivity will determine the effectiveness of energy conversion to magnetic forces. As material conductivity decreases, energy losses occur due to heating of the workpiece. A more conductive material, such as copper or aluminum, will be deformed more than steel at the same energy level.

This equipment has been used to remove the distortion from welded bulkheads in the Saturn first stage. It appears to be most suitable for use in applications where small deflections are required to correct distortion. In principle, such equipment could be useful in the shipbuilding industry, but considerable research would be needed to develop tooling for handling high-strength steels in the thicknesses used in ship fabrication. This equipment is not suitable for shipyard use in its present form.

REFERENCES (TO APPENDIX A)

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(2) Inman, N., Pfanner, and Smith, F., "Magnetic Forming Coil Design and Development", Republic Aviation Corporation, Farmingdale, N. Y., Final Report to George C. Marshall Space Flight Center, Huntsville, Alabama, Contract No. NAS 8-5435 (March, 1964).

(3) Waniek, R. W., Furth, H. P. et al., "Magnetic Forming Coil Design and Development", Advanced Kinetics, Inc., Summary Report to George C. Marshall Space Flight Center, Huntsville, Alabama. Contract No. NAS 8-5434 (April, 1964).

(4) "Electromagnetic Hammer", Report No. NASA SP-503 , Technology Utilization Division, National Aeronautics and Space Administration, Washington, D.C. (December, 1965).

APPENDIX B.

RESULTS OF DROP-WEIGHT TEAR TESTS

The results of the Drop-Weight Tear Tests for unwelded and welded samples appear in Table B-1 and B-2 respectively. Hardness data appear in Table B-3.

Table B1. Drop-Weight Tear Test Results for Unwelded Samples

Amount of Distortion, in.	Mechanical Straightening Temperature, F	Thermal Straightening Temperature, F	Test Temperature, F	Energy Ft-lbs.	Shear Area, Percent
		Steel A517, Grade A, ½-in thick			
-	-	-	+50	2400	100
			0	2310	100
			-40	1420	85
			-50	1040	64
			-50	1240	78
			-60	855	38
			-60	1090	38
			-70	815	25
			-100	530	23
7/16	1300	-	-10	2050	100
			-50	1975	100
			-70	1540	100
			-90	1700	99
			-130	990	19
"	1000	-	-10	1650	100
			-50	1725	100
			-60	1440	99
			-70	965	50
			-80	1040	38
"	RT	-	-10	1700	100
			-40	1460	99
			-50	1220	70
			-60	1220	94
			-70	830	29
9/64	1300	-	-10	1975	100
			-50	2100	100
			-60	1950	100
			-70	1340	78
			-80	1120	38
"	RT	-	-10	1825	100
			-50	1460	100
			-60	1370	92
			-70	880	38
			-80	815	28

Table B1. Drop-Weight Tear Test Results for Unwelded Samples (Continued)

Amount of Distortion, in.	Mechanical Straightening Temperature, F	Thermal Straightening Temperature, F	Test Temperature, F	Energy Ft-lbs.	Shear Area, Percent
		Steel A517, Grade A, ½-in thick			
7/16	-	1300-1400	+120	1650	92
			+90	1175	50
			+60	815	46
			+30	855	48
			-10	460	14
"	-	1100-1200	+60	1460	80
			+30	1370	62
			+10	965	55
			-10	460	12
			-30	240	6
		Steel A517, Grade A, 3/8-in thick			
-	-	-	0	1315	100
			-50	1290	100
			-60	940	94
			-70	730	90
			-70	705	78
			-80	565	45
			-80	530	50
			-90	460	39
			-100	460	30
1/2	1200	-	-30	1290	100
			-60	1015	100
			-70	640	75
			-80	815	55
			-90	340	32
"	RT	-	-30	1460	100
			-40	1150	100
			-70	910	80
			-80	505	45
			-90	310	12
"	-	1100-1200	+70	1090	95
			+60	1015	82
			+30	600	50
			+10	600	65
			-30	340	16
1/2	-	1300-1400	+150	990	90
			+100	280	2
			+60	280	2
			+10	240	2
			-30	210	2

Table B1. Drop-Weight Tear Test Results for Unwelded Samples (Continued)

Amount of Distortion, in.	Mechanical Straightening Temperature, F	Thermal Straightening Temperature, F	Test Temperature, F	Energy Ft-lbs.	Shear Area, Percent
		Steel A537, Grade A, 1/2-in thick			
-	-	-	+100	3250	100
			+50	3160	100
			+30	3140	100
			+20	1540	92
			+10	1090	88
			0	940	67
			-10	680	29
			-30	460	11
			-50	260	4
7/16	1200	-	+30	2100	100
			+20	1900	92
			0	1750	75
			-10	1090	60
			-20	620	16
"	RT	-	+40	2650	100
			+30	1650	80
			+20	1340	63
			+10	765	33
			0	530	12
7/16	-	1300-1400	+50	2270	100
			+40	1900	92
			+30	1480	87
			+20	830	40
			0	660	11
"	-	1100-1200	+50	2610	95
			+40	2290	94
			+20	1540	50
			0	1065	40
			-10	815	31
		Steel A441, Grade A, 1/2-in thick			
-	-	-	+100	1240	100
			+60	1150	100
			+50	965	87
			+40	940	84
			+30	390	40
			+20	240	8
			0	240	4
			-50	210	2

Table B1. Drop-Weight Tear Test Results for Unwelded Samples (Continued)

Amount of Distortion. in.	Mechanical Straightening Temperature, F	Thermal Straightening Temperature, F	Test Temperature, F	Energy Ft-lbs.	Shear Area, Percent
		Steel A441, Grade A, 1/2-in thick			
7/16	1200	-	+80	1175	98
			+70	1150	95
			+60	880	80
			+56	460	39
			+20	260	7
"	RT	-	+80	1200	99
			+70	1090	94
			+60	990	93
			+50	815	70
			+20	240	9
"	-	1300-1400	+100	1420	100
			+70	1340	100
			+50	1040	82
			+40	1040	80
			+20	280	4
"	-	1100-1200	+100	1480	100
			+70	1150	70
			+50	680	55
			+20	600	45
			0	390	29
		Steel ABS-B, Grade A, 1/2-in thick			
-	-	-	+150	4200	100
			+100	3360	100
			+70	2400	100
			+60	1440	78
			+60	1725	88
			+50	640	33
			+40	210	8
			0	210	5
			-50	210	2
7/16	1200	-	+90	2100	97
			+80	1925	94
			+70	1540	78
			+60	855	26
			+50	765	23
"	RT	-	+120	2630	100
			+100	1825	85
			+90	1480	78
			+80	830	44
			+60	365	7

Table B1. Drop-Weight Tear Test Results for Unwelded Samples (Continued)

Amount of Distortion, in.	Mechanical Straightening Temperature, F	Thermal Straightening Temperature, F	Test Temperature, F	Energy Ft-lbs.	Shear Area, Percent
Steel ABS-B, Grade A, 1/2-in thick					
	-	1300-1400	+100	3180	98
			+90	3000	92
			+80	1900	75
			+70	1090	50
			+50	830	19

Table B2. Drop-Weight Tear Test Results for Welded Samples

Amount of Distortion, in.	Mechanical Straightening Temperature, F	Thermal Straightening Temperature, F	Test Temperature, F	Energy, Ft-lbs.	Shear Area, Percent
Steel A517, Grade A, 1/2-in thick					
-	-	-	+50	2100	100
			0	1400	100
			-10	1150	90
			-20	1150	100
			-20	940	88
			-30	1220	100
			-30	830	82
			-40	680	52
			-50	505	29
7/16	1300	-	-10	1975	100
			-20	2210	100
			-30	2100	100
			-40	2210	100
			-50	1265	21
"	1000	-	+10	1825	100
			-10	1090	80
			-30	1850	100
			-40	1420	90
			-50	600	24
"	RT	-	-10	1370	100
			-40	1440	100
			-50	855	60
			-60	705	37
			-70	640	28

Table B2. Drop-Weight Tear Test Results for Welded Samples (Continued)

Amount of Distortion, in.	Mechanical Straightening Temperature, F	Thermal Straightening Temperature, F	Test Temperature, F	Energy Ft-lbs.	Shear Area, Percent
		Steel A517, Grade A, 1/2-in thick			
9/64	1300	-	-10	1570	92
			-30	1800	100
			-40	1120	85
			-50	1600	48
			-60	480	38
"	RT	-	-10	1750	100
			-30	1175	88
			-40	1290	98
			-50	565	42
			-60	600	38
7/16	-	1300-1400	+80	1265	85
			+60	1200	80
			+30	990	60
			-10	660	55
			-30	260	6
"	-	1100-1200	-10	1600	100
			-20	705	27
			-30	680	22
			-40	815	19
			-50	390	14
		Steel A517, Grade A, 3/8-in thick			
-	-	-	+50	1015	100
			0	1040	100
			-10	1015	100
			-20	990	100
			-20	480	70
			-30	990	100
			-30	310	50
			-60	60	39
			-70	120	21
1/2	1200	-	-10	1460	100
			-20	705	60
			-30	640	53
			-40	880	82
			-50	530	21
"	RT	-	-10	1090	100
			-40	640	70
			-50	765	88
			-60	705	60
			-70	340	30

Table B2. Drop-Weight Tear Test Results for Welded Samples (Continued)

Amount of Distortion, in.	Mechanical Straightening Temperature, F	Thermal Straightening Temperature, F	Test Temperature, F	Energy Ft-lbs.	Shear Area, Percent
		Steel A517, Grade A, 3/8-in thick			
1/2	-	1300-1400	+150	1040	95
			+90	415	35
			+60	260	43
			+30	240	48
			-10	240	21
"	-	1100-1200	+60	1240	100
			+50	1200	100
			+40	440	43
			+30	390	42
			-10	310	21
		Steel A537, Grade A, 1/2-in thick			
-	-	-	+100	2480	100
			+50	1800	98
			+40	1800	97
			+10	1600	90
			0	1175	60
			-20	1240	44
			-30	600	35
			-40	240	22
			-50	180	13
7/16	1200	-	+20	1750	95
			+10	1370	87
			0	1340	85
			-10	855	46
			-20	800	33
"	RT	-	+40	1650	90
			+30	1400	85
			+20	1015	42
			+10	730	45
			0	1290	39
"	-	1300-1400	+50	2800	100
			+30	1600	92
			+20	1240	74
			0	880	60
			-10	340	16
"	-	1100-1200	+50	1950	100
			+30	1800	93
			+20	1700	82
			0	1240	45
			-10	910	38

Table B2. Drop-Weight Tear Test Results for Welded Samples (Continued)

Amount of Distortion, in.	Mechanical Straightening Temperature, F	Thermal Straightening Temperature, F	Test Temperature, F	Energy Ft-lbs.	Shear Area, Percent
		Steel A441, Grade A, 1/2-in thick			
-	-	-	+150	1240	100
			+100	1240	100
			+80	990	96
			+0	940	84
			+60	880	73
			+50	640	60
			+40	440	48
			+30	390	46
			+20	210	24
7/16	1200	-	+80	1120	100
			+70	1090	94
			+60	440	38
			+50	480	43
			+20	390	34
"	RT	-	+90	1090	100
			+80	910	82
			+70	460	61
			+50	600	42
			+20	210	7
"	-	1300-1400	+100	1315	100
			+70	1175	100
			+50	880	87
			+40	990	85
			+20	310	6
"	-	1100-1200	+100	1460	100
			+70	1340	92
			+50	990	80
			+20	830	68
			0	1065	88
		Steel ABS-B, Grade A, 1/2-in thick			
-	-	-	+150	3500	100
			+100	2360	100
			+80	1825	100
			+80	1240	88
			+70	1750	100
			+70	705	64
			+60	505	48
			+50	480	34
			+40	340	18

Table B2. Drop-Weight Tear Test Results for Welded Samples (Continued)

Amount of Distortion, in.	Mechanical Straightening Temperature, F	Thermal Straightening Temperature, F	Test Temperature, F	Energy Ft-lbs.	Shear Area, Percent
		Steel ABS-B, Grade A, 1/2-in thick			
7/16	1200	-	+90	2310	86
			+86	1775	85
			+50	2880	90
			+40	415	23
			+20	280	4
"	RT	-	+120	1700	95
			+90	1340	90
			+80	910	52
			+70	660	47
			+60	310	8
"	-	1300-1400	+100	3480	100
			+90	2560	100
			+80	1650	94
			+70	940	65
			+50	705	21
"	-	1100-1200	+100	2735	95
			+70	2480	100
			+50	1480	95
			+30	1150	75
			+20	560	30

Table B3. Approximate Ultimate Strength Obtained by Conversion

Code	Material	Treatment	Hardness R_A Unwelded(1)	Welded(1)	As received(2)
1	A517, 1/2"	None	57.9 (101 ksi)	58.2 (101 ksi)	62.5 (24 R_C)
2	"	M1300	54.7 (87 ksi)	54.1 (84 ksi)	(117 ksi)
3	"	M1000	53.3 (82 ksi)	56.5 (91 ksi)	
4	"	MRT	57.2 (97 ksi)	59.7 (107 ksi)	
7		T1350	56.6 (93 ksi)	51.7 (78 ksi)	
8	"	T1150	57.0 (96)	58.4 (102)	
17	A537, 1/2"	None	46.4	42.2	45 (72 R_B)
18	"	M1200	41.9	40.5	
19	"	MRT	48.2	44.4	
20	"	T1350	46.1	47.5	
20a	"	T1150	41.1	46.6	
21	A441, 1/2"	None	46.0	46.1	53 (86 R_B)
22	"	M1200	42.8	44.6	
23	"	MRT	45.8		
24	"	T1350	47.1	45.0	
24a	"	T1150	46.2	45.5	
25	ABS-B, 1/2"	None	39.9	41.8	46.5 (75 R_B)
26	"	M1200	38.3	44.4	
27	"	MRT	43.8	37.3	
28	"	T1350	45.9		
28a	"	T1150		43.9	

(1) Hardness obtained by averaging values at 1/2, 1, 2" from fracture. On welded samples, the 1/2" value was not consistently different from 1" & 2" values.

(2) Hardness measured on polished cross section, see comments on page 24.

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	Naval Ship Systems Command

13. ABSTRACT

An experimental study was conducted to determine the effects of mechanical straightening and flame straightening on the properties of steels used in shipbuilding. The steels investigated during this program included an ordinary carbon steel (ABS-B), two low-alloy, high-strength steels (A441 and A537), and a quenched and tempered steel (A517, Grade A). The removal of distortion in unwelded and welded test plates was accomplished by (1) mechanical straightening at room temperature, 1000 F, 1300 F, and (2) flame straightening in the temperature ranges of 1100-1200 F and 1300-1400 F. Controlled amounts of distortion were provided in unwelded plate by mechanical bending; distortion in welded plates was provided by jigging the restraint control. Drop-weight tear tests were conducted to assess the effect of the straightening parameters on the notch-toughness behavior of the respective steels.

A summary report on flame straightening was prepared and distributed earlier during this program. This report discussed the nature of distortion and of flame straightening and was published as Report SSC-198. However, since very little information in the literature pertains directly to possible material degradation caused by flame straightening, the experimental studies described in this report were undertaken.

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